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## Synthetic mammalian neuromuscular junction and method of making (US)

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- (54) **SYNTHETIC MAMMALIAN NEUROMUSCULAR JUNCTION AND METHOD OF MAKING**
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See application file for complete search history.

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#### (57) ABSTRACT

A method for forming neuromuscular junctions includes forming functional neuromuscular junctions between motoneurons and muscle cells by co-culturing one or more human motoneurons and one or more human muscle cells in a substantially serum-free medium. A synthetic mammalian neuromuscular junction includes a human motoneuron functionally linked to a human muscle cell in a substantially serum-free medium. An artificial substrate may be used to support the one or more neuromuscular junctions.

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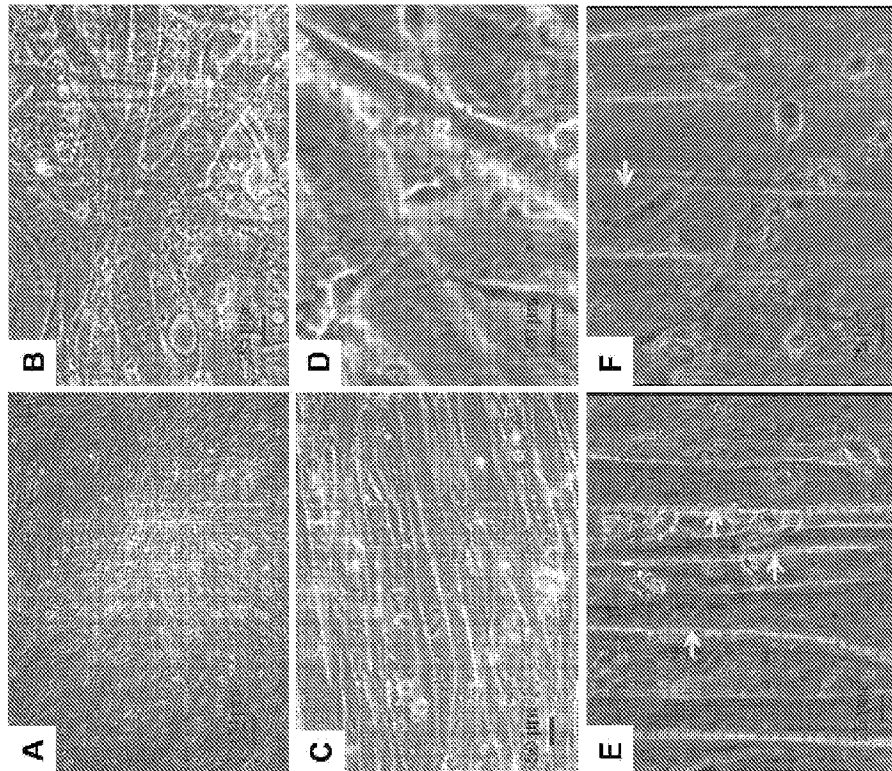
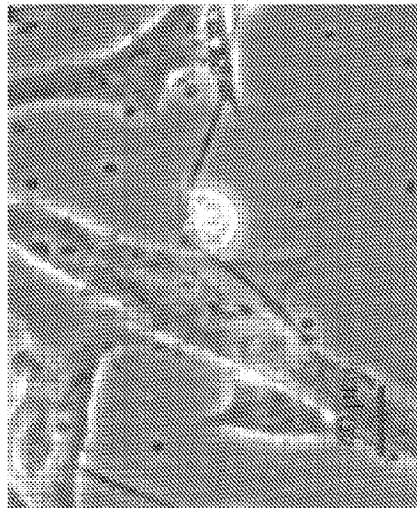
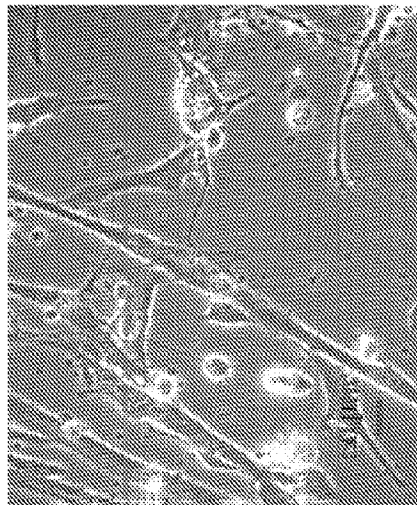


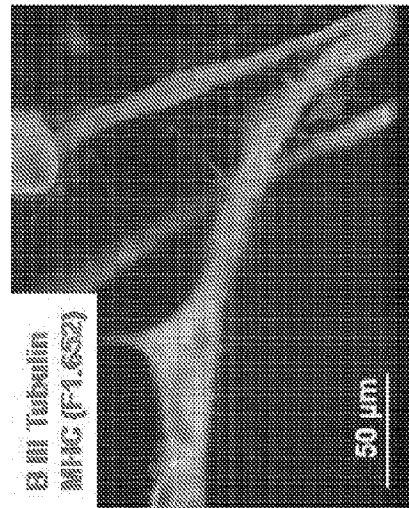
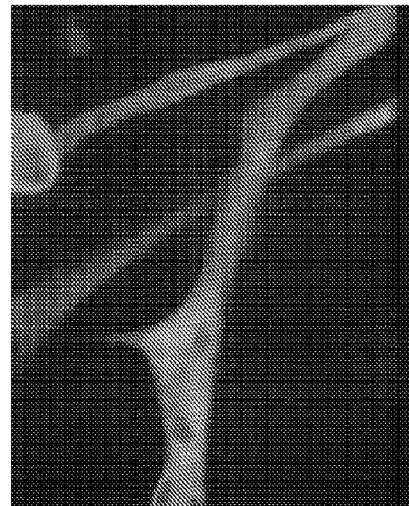
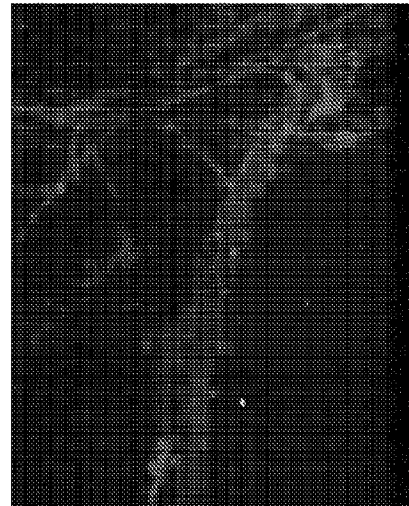
FIG. 1



**B**



**A**



3 M Tubulin  
MHC (F-1.652)

**C**

FIG. 2

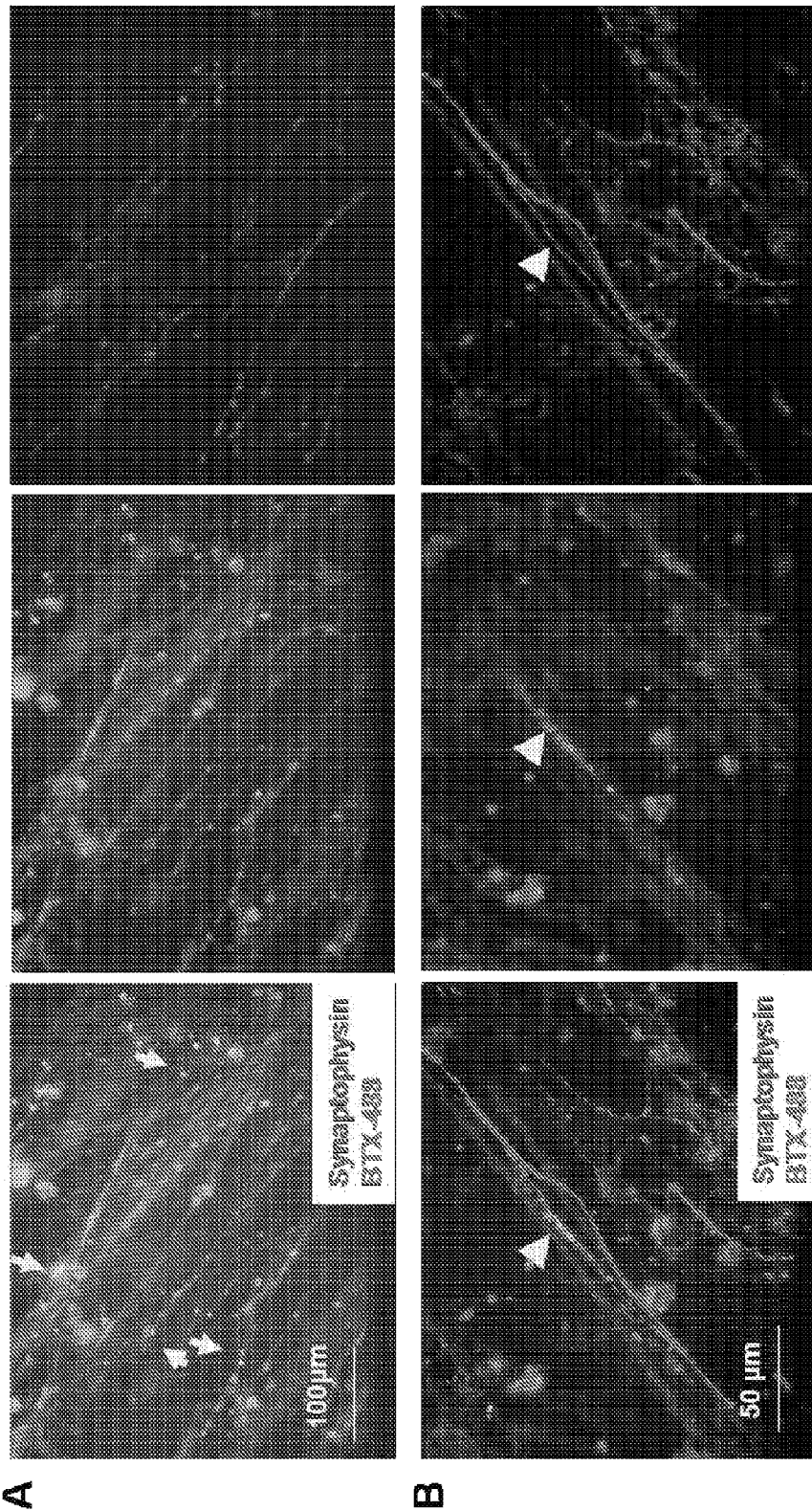


FIG. 3



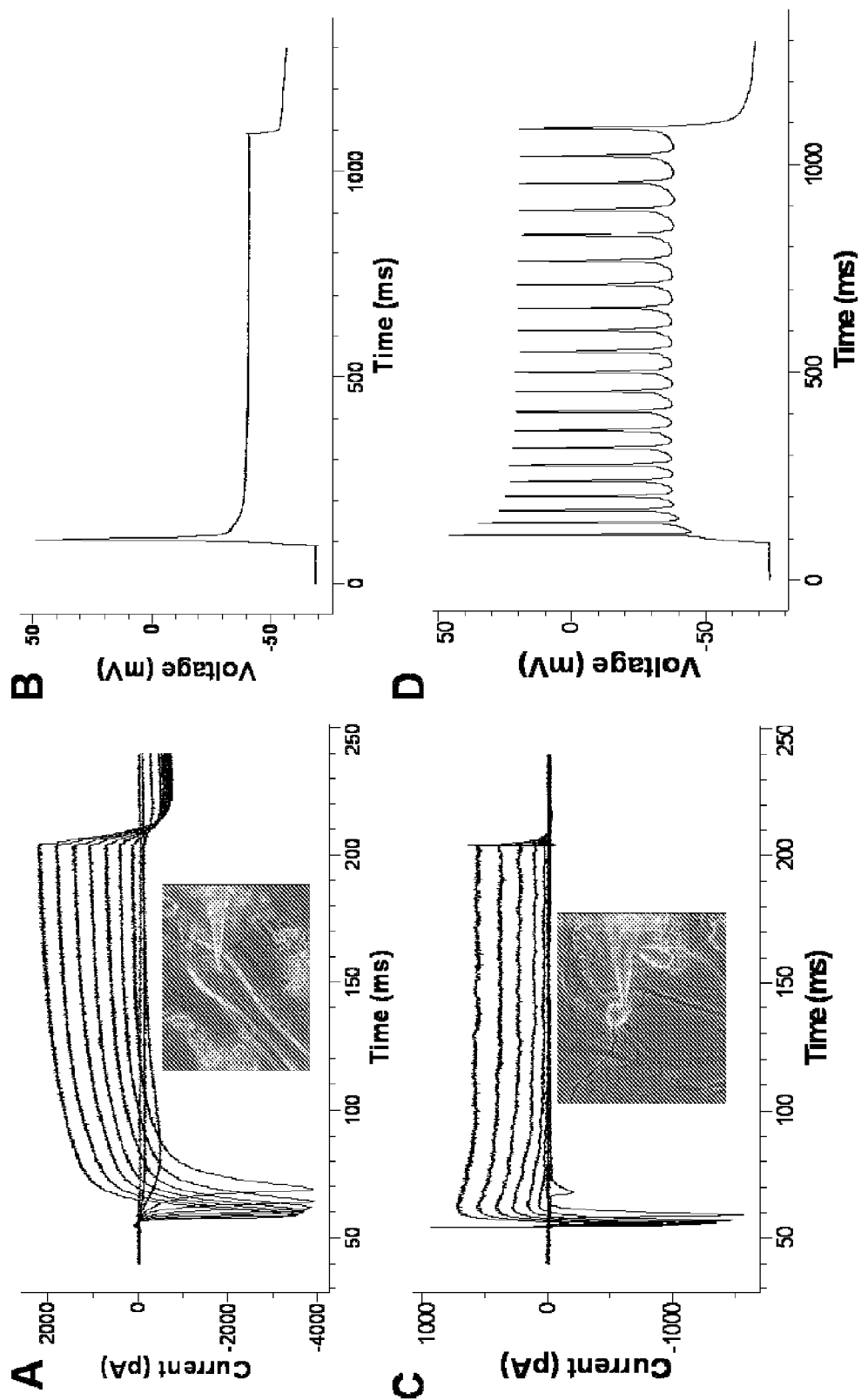


FIG. 4

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# SYNTHETIC MAMMALIAN NEUROMUSCULAR JUNCTION AND METHOD OF MAKING

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a National Phase Application of International Application No. PCT/US2011/035585, filed May 6, 2011, which claims priority to U.S. Patent Application No. 61/332,003, filed May 6, 2010, and is a continuation-in-part of U.S. patent application Ser. No. 12/765,996, filed Apr. 23, 2010, which in turn claims priority to U.S. Patent Application No. 61/171,958, filed on Apr. 23, 2009, the entire contents of which are incorporated herein fully by this reference.

## STATEMENT OF GOVERNMENT INTEREST

The invention claimed herein was made with at least partial support from the U.S. Government under National Institutes of Health grant R01NS050452. Accordingly, the U.S. Government may have certain rights in the invention.

## FIELD OF THE INVENTION

The invention relates to the field of cell culture, and, more particularly, to formation of neuromuscular junctions.

## BACKGROUND OF THE INVENTION

Neuromuscular junction ("NMJ") formation is a complex process that depends on many variables. Unfortunately, current techniques for producing NMJs suffer from one or more drawbacks which hinder their reproducibility and utility.

For centuries, animals and animal-derived tissues have been the major tools for understanding biological systems, human diseases, developing therapeutic strategies and screening drugs. However, translating animal data to clinical applications has been problematic, leading to fewer drugs being approved and an increasing cost in the drug discovery process (58). While some functional in vitro systems composed of human cells has been reported for liver (59), skin (60,61) and cardiomyocytes (62,63), no system composed of human cells has been reported for neuronal systems. Systems based on functional NMJs are of particular interest due to the fact that NMJs represents a synapse-based model that would be clinically applicable to spinal cord injury and motoneuron-related diseases such as Amyotrophic lateral sclerosis ("ALS") (64), spinal muscle atrophy (65) and muscular dystrophy (66). An in vitro (1) co-culture system composed of human motoneurons and skeletal muscle would be useful for studies ranging from understanding NMJ synaptogenesis, target generation for NMJ related diseases, screening therapeutic candidates and conducting drug toxicology evaluation. The advantages of human-based in vitro systems compared to in vivo systems reside in that they are much simpler and therefore easy to manipulate any factors, to dissect the mechanisms or pathways and to analyze the results.

One technique for forming NMJs in vitro to use a motoneuron ("MN")-muscle cell co-culture. MN-muscle co-cultures have been described in *Xenopus* (1, 2), chick (3-5), mouse (6, 7) and rat (8, 9), as well as in cross-species investigations between mouse MN-chick muscle (7, 10), human stem cell-derived MNs-myotubes from C2C12 cells (11). One drawback to these in vitro MN-muscle co-culture systems is that they use serum containing media and a biological substrate (3-5,8,9). Since the serum containing medium con-

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tains many unknown components and because of the technical difficulties in creating reproducible biological substrates, these examples have led to undesired culture variability, making it extremely difficult, if not impossible, to ascertain the minimum factors required for recreating or maintaining the NMJ in vitro.

Due to the variability inherent with serum containing media (12), serum-free NMJ formation systems have been developed. NMJ formation in serum-free systems has been demonstrated using rat cells (13). Also, cross species NMJ formation between human MN and rat muscle (14) has been demonstrated. These in vitro systems comprised of animal-derived components have provided the scientific community with readily available models for understanding NMJ synaptogenesis and NMJ-related diseases, however, in order to understand NMJ formation in all human cells, the results from these systems must be extrapolated, which can be disadvantageous for clinical applications among others.

A major hurdle in building in vitro biological systems using human components is limitations related to tissue source. However, recent developments in stem cell biology provide an avenue to, not only have an unlimited supply of human cells for tissues, but also to provide genetic diversity in the systems. Cloned human skeletal muscle satellite cells have been used for studying NMJs in vitro by combining them with rat spinal explants or dissociated MN in serum-containing systems (15-19). MNs derived from human embryonic stem cells ("hESC") (11) and human fetal spinal cord stem cells ("hSCSC") (20) have been studied. NMJ formation has been (2) demonstrated between hESCs and C2C12 cells in a serum based system (11), as well as between hSCSCs and rat myotubes derived from embryonic skeletal muscles in a defined serum-free system (14). However, no human based in vitro NMJ system, in which both MNs and myotubes were derived from stem cells presently exists. Accordingly, there is a need in the art for a human based system for NMJ formation that does not suffer from one or more of the above described drawbacks.

## SUMMARY

Certain embodiments of the invention are directed to methods that satisfy the need for a human based NMJ formation system. In one exemplary embodiment, the method comprises forming functional neuromuscular junctions between motoneurons and muscle cells by co-culturing one or more human motoneurons and one or more human muscle cells in a substantially serum-free medium.

In another embodiment the method comprises suspending human skeletal muscle cells in a serum-free medium; suspending human motoneurons derived from human spinal cord stem cells in the serum-free medium; plating the suspended muscle cells and the suspended motoneurons onto an artificial carrier; and monitoring for formation of functional neuromuscular junctions.

Other embodiments of the invention are directed to neuromuscular junctions that satisfy this need. In one example, the embodiment is directed to synthetic mammalian neuromuscular junction comprising a human motoneuron functionally linked to a human muscle cell in a substantially serum-free medium. The human motoneuron can be functionally linked to the human muscle cell on an artificial surface. A preferred artificial surface has a silicon based monolayer substrate deposited thereon, which may, if desired, be deposited in a predetermined pattern.

In certain embodiments, the substantially serum-free medium is completely serum free. Some examples of the

substantially serum-free medium comprise at least one synaptogenesis promoting component and one or more trophic factors. NbActiv4 can be added to the serum-free medium. In a preferred embodiment, the medium comprises the components in Table 1.

Preferably, but not necessarily, the human motoneuron cells are derived from human spinal cord stem cells and the human muscle cells are derived from human skeletal muscle stem cells.

Some embodiments can include a synthetic substrate adapted to support at least one neuromuscular junction thereon. The synthetic substrate is preferably silicon based and more preferably is DETA. The synthetic substrate may be deposited on a support surface in a predetermined pattern if desired. The synthetic substrate may be coated on a carrier.

These and other objects, aspects, and advantages of the present invention will be better appreciated in view of the drawings and following detailed description of the preferred embodiments.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a set of phase contrast microscopy images showing human skeletal muscle cells (hSKMs) and human motoneurons (hMNs) in culture and co-culture, according to an embodiment of the present invention; A. Depicts myocytes that were allowed to grow to confluency before differentiation was induced; B. Depicts, multi-nuclei myotubes that were induced during differentiation; C. Depicts both myotubes and neurons that survived in the coculture; D. Illustrates connections between neurons and myotubes in the co-culture (indicated by arrows); E. Shows the striation of myotube as indicated by the yellow arrow; F. Illustrates a neuron with MN morphology sends out long axons towards a striated myotube as indicated by the red arrow;

FIG. 2 is a set of microscopy images showing that after one week of co-culture the morphology of hMNs and hSKM myofibers were well defined and easily distinguishable; A & B. Shows a neuron sent an axon towards a myotube and branched at the contacts with myotubes as indicated by the arrows; C. Depicts co-immunostaining of MHC (myosin heavy chain) with  $\beta$  III Tubulin in a 19 day co-culture;

FIG. 3 is a set of microscopy images depicting synaptophysin-positive terminals co-localized with AchR clusters; potential synaptic sites (yellow arrows) demonstrated by co-localization of nerve terminals (indicated by synaptophysin) and AchR (indicated by BTX488), in a day 15 coculture—Scale Bars A. 20 $\times$ . B. 40 $\times$ ; and

FIG. 4 is a representative graph of voltage-clamp and current-clamp recordings for the MNs and myotubes; A&B. Representative Voltage clamp (A) and Current clamp (B) trace recording on myotubes in the co-culture; C&D. Representative Voltage clamp (C) and Current clamp (D) trace Recording on motoneurons in the co-culture.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In the Summary of the Invention above and in the Detailed Description of the Invention and in the accompanying drawings, reference is made to particular features (including method steps) of the invention. It is to be understood that the disclosure of the invention in this specification includes all possible combinations of such particular features. For example, where a particular feature is disclosed in the context of a particular aspect or embodiment of the invention, that feature can also be used, to the extent possible, in combina-

tion with and/or in the context of other particular aspects and embodiments of the invention, and in the invention generally.

The term “comprises” is used herein to mean that other ingredients, features, steps, etc. are optionally present. When reference is made herein to a method comprising two or more defined steps, the steps can be carried in any order or simultaneously (except where the context excludes that possibility), and the method can include one or more steps which are carried out before any of the defined steps, between two of the defined steps, or after all of the defined steps (except where the context excludes that possibility).

In this section, the present invention will be described more fully with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

According to an embodiment of the invention, an in vitro system for forming NMJs between human cells is provided. The system comprises an in vitro co-culture adapted to allow NMJs to form between human neurons and human muscle cells in a defined environment. The defined environment is preferably achieved by utilizing a co-culture medium in which the ingredients and quantities of those ingredients are known. In a preferred embodiment, the medium contains no serum. The co-culture can also be prepared on substrate that has a defined surface, such as by assembling a synthetic material onto an underlying surface for example. In some cases, the synthetic material can be assembled on the underlying surface according to a desired pattern.

In vitro NMJ co-culture systems containing human cellular components have been reported previously. Human stem cell-derived motoneurons can form NMJs when co-cultured with C2C12 cells (11) from co-cultures of embryonic rat spinal explants with human SKM stem cell-derived myofibers (17, 32), but in serum containing media. One study also investigated human stem cell derived motoneuron innervations for rat embryonic SKM in a defined system (14). These systems were employed to study the functional integrity of motoneurons differentiated from human stem cells (11, 14), to investigate the functional maturation process of SKMs derived from human SKM stem cells (33, 34), the mechanisms of NMJ formation on human SKMs (15-19, 30-36), and the pathogenesis of some spinal muscular diseases (37).

This disclosure reports the first human-based in vitro NMJ system which supports the differentiation of human stem cell derived motoneurons and SKMs and provides for functional NMJ formation. The system developed in this study, by the co-culture of human stem cell-derived motoneurons and SKMs, provides a system closer to the human condition that is capable of addressing the above described drawbacks, as well as neurological and/or muscular disease modeling, drug discovery and regenerative medicine.

In an exemplary embodiment, the human neurons are MNs differentiated from human spinal cord stem cells and the muscle cells are human skeletal muscle stem cells.

By way of example, a suitable co-culture medium that can be used in the human NMJ formation system is comprised of the ingredients provided in Table 1. The scope of the invention is not limited only to these ingredients, nor is it required that every one of the ingredients be used in every embodiment. Ingredients may be added to or taken away from Table 1 without falling outside the scope of the invention. The combination of NEUROBASAL™ medium, B27, Glutamax, GDNF, BDNF, Shh, RA, IGF-1, cAMP, CNTF, NT-3, NT-4, Vitronectin and Laminin has been found to be able to support the growth, differentiation, and long-term survival of MNs

derived from human stem cells (11, 14). Laminins are important components of the extracellular matrix that facilitates synaptogenesis (1). Specifically,  $\beta 2$  laminins are concentrated at synaptic sites and are useful for their postnatal maturation (57). The addition of the G5 supplement to the co-culture medium has been found to significantly enhance myocyte proliferation. However, the continuous presence of these trophic factors, including BDNF, GDNF, NT-3, NT-4 and cAMP, was found to significantly down regulate agrin deposition along the neurites and at nerve-muscle contacts, thus preventing synaptogenesis (2).

In a preferred preparation of NMJs, the trophic factors were gradually withdrawn and the culture was fed using only NbActiv4 media. The NbActiv4 media formula was generated by adding three ingredients, cholesterol, estrogen, and creatine to media containing NEUROBASAL™, B27 and Glutamax (53). There is evidence that the addition of these ingredients can significantly promote synaptogenesis (53-56). Therefore, the co-culture was first plated in the co-culture medium to ensure the survival and growth of MNs and myocytes, followed by the gradual withdrawal of these factors which enabled the reciprocal induction between the MNs and myotubes that naturally occurs in development.

Advantageously, the defined co-culture medium delineates the basis for the essential components during NMJ formation, and provides a basic system for dissecting the individual factors, for investigating the underlying mechanisms, and later for treatment of diseases related to the cellular components of NMJs.

A preferred substrate is trimethoxysilylpropyldiethylenetri-amine ("DETA"), which can be coated onto a carrier or surface such as a glass cover slip for example. In the working examples discussed below, DETA was coated on a glass surface to form a self-assembled monolayer. DETA has previously been shown to support neuronal (26), skeletal muscle (27), endothelial (38), and cardiac cell growth (39), and has been used in creating high-resolution, in vitro patterned circuits of embryonic hippocampus neurons (40). Moreover, DETA substrates have been shown to promote guided axonal growth and direct axonal and dendritic process extension at the level of a single neuron (41). Therefore, the successful formation of NMJ on this substrate implies that some co-cultures of the invention can be patterned at high resolution to study engineered in vitro NMJs. Especially, this surface modification technique can be used for guiding specific NMJ formation.

Functional in vitro systems composed of human cells in a defined, serum-free system, especially those reproducing fundamental neurological processes, will be a significant component in transforming current methods of drug discovery and toxicology. The utilization of neuronal systems derived from stem cells enables a process that can be genetically diverse, yet source reproducible. The use of a defined, serum-free system also enables the integration into the next generation of high-content and ultimately high-throughput screening technologies.

Accordingly, embodiments of the invention have many advantages. Some, but not all, of those advantages are listed here. Not all of these advantages are required by all embodiments of the invention. In summary, embodiments of the invention provide the first pure human based NMJ in vitro culture system. This human cell-based system bridges the gap between findings from animals and their clinical applications. The stem cell origin for both motoneurons and skeletal muscles enables the formation of these cultures in large quantities which can be important for high throughput drug screening. The serum-free medium allows this system to be

highly re-producible and easy to manipulate. The patternable surface gives the power to the system to be engineered into neural circuits. These attributes indicate that this system will facilitate not only the studies concerning human NMJ development and regulation, both in vitro and in vivo, but also the research fields targeting NMJ-related diseases and treatment, such as by developing high information content drug screen systems and test beds in pre-clinical studies.

In the following section, we describe several working examples in which an exemplary human NMJ model system embodiment was characterized by morphology, immunocytochemistry, and electrophysiology. Further, NMJ formation was demonstrated by immunocytochemistry and videography.

## WORKING EXAMPLES

### DETA Surface Modification

Glass coverslips (6661F52, 22×22 mm No. 1; Thomas Scientific, Swedesboro, N.J., USA) were cleaned using HCl/methanol (1:1) for at least 2 hours, rinsed with water, soaked in concentrated H<sub>2</sub>SO<sub>4</sub> for at least 2 hours and rinsed with water. Coverslips were boiled in nanopure water and then oven dried. The trimethoxysilylpropyldiethylenetri-amine (DETA, T2910KG; United Chemical Technologies Inc., Bristol, Pa., USA) film was formed by the reaction of cleaned surfaces with a 0.1% (v/v) mixture of the organosilane in freshly distilled toluene (T2904; Fisher, Suwanne, Ga., USA). The DETA coated coverslips were heated to ~80° C., then cooled to room temperature (RT), rinsed with toluene, reheated to approximately the same temperature, and then cured for at least 2 hours at 110 C. Surfaces were characterized by contact angle and X-ray photoelectron 5 spectroscopy as described previously (26, 42, 43).

### Co-Culture of Human MNs and Human Skeletal Muscle Stem Cells

#### Materials and Methods.

The human spinal cord stem cell line was isolated and established as described in (44-46). MNs were differentiated from this cell line as described in (20). Briefly, ~1×10<sup>6</sup> hSC-SCs were plated in one 60 mm paranox cell culture dish (Nunc, Cat #174888) and differentiated 4 days in the priming media followed by 6 days in differentiation media. The composition of the priming media and differentiation media were described in (20).

Human skeletal muscle stem cells (hSKM SCs) were isolated, proliferated and differentiated as described in (47). Briefly, primary human skeletal muscle cells isolated by needle biopsy (48) were expanded in myoblast growth medium (MGM; SkGM (Cambrex Bio Science, Walkersville, Md.) plus 15% (v/v) fetal bovine serum). Biopsies were performed on adult volunteers according to procedures approved by the Institutional Clinical Review Board of the Miriam Hospital. Cell preparations on average were 70% myogenic based on desmin positive staining (49). Myoblast fusion into postmitotic myofibers was induced by incubation in differentiation medium (high-glucose DMEM (Invitrogen, Carlsbad, Calif.) supplemented with insulin (10  $\mu$ g/ml), bovine serum albumin (50  $\mu$ g/ml), epidermal growth factor (10 ng/ml) and gentamicin (50  $\mu$ g/ml)). For each culture, hSKM SCs were plated on DETA coverslips at a density of 20 cells/mm<sup>2</sup> in hSKM Growth Medium (Lanza, Cat# CC-3160), fed every 2 days by changing the whole medium. On day 7, myoblast fusion was induced by switching to differentiation medium. The cells were fed every 2 days by changing half of the medium. On day 7 after differentiation, differentiated hSCs

were harvested and plated on top of these induced myotubes in a density of 200 cells/mm<sup>2</sup>, and the medium was changed to co-culture medium (Table 1). Two days later, the medium was fed by co-culture medium (without G5) by changing half of the medium. After another two days and thereafter, the cultures were fed by NbActiv4 (Brain Bits) by changing half of the medium.

#### Discussion.

The procedure of co-culturing motoneurons and skeletal muscles (SKMs) was described in detail in the Material and Methods. Briefly, human SKM stem cells were allowed to grow to confluence before induction of differentiation (FIG. 1A). After switching to differentiation media, the fusion of myocytes was initiated. Multi-nuclei myotubes formed gradually and were prevalent from day 4 in the culture (FIG. 1B). Differentiated human motoneurons (hMNs) were cultured as in Guo et al. (20) and were plated on the top of the differentiated myotubes and the medium was switched to a co-culture medium at this time. Both hSKMs and hMNs survived well in the co-culture media (FIG. 1C). Also, the differentiation of both hMNs and hSKMs were evident after one week. The hMNs were easily identifiable in the co-culture and sent out axons either along or ending at the myotubes (FIGS. 1D, E). In addition, a large number of human myotubes exhibited striated band patterns (FIGS. 1E, F). This characteristic A & I band patterning is caused by differential light diffraction due to the organization of myofibrillar proteins forming sarcomeres within the myotubes, and is observed with mature *in vivo* muscle fibers (21, 22). The striated patterns indicated the formation of the basic contractile apparatus for skeletal muscle, implying that these myofibers were structurally and functionally mature.

Multiple plating conditions were examined to determine the optimal culturing procedures. When plating differentiated motoneurons on top of SKMs before extensive myotube formation the myocyte fusion proceeded sub-optimally when switched to the co-culture medium, and with the formation of a minimal number of multi-nuclei myotubes. The viability and morphological differentiation of the replated motoneurons was also poor, overall indicating that the co-culture media is not favorable for the fusion of human myocytes, and the successful replating of motoneurons required the pre-differentiation of the SKMs. This is reasonable considering that muscle cells release the neurotrophins BDNF, GDNF and NT-3/4 to support MN survival and attract neurite outgrowth of motoneurons during development (23-25).

Another observation was that when the co-culture was fed for four days with co-culture medium containing G5, undesired proliferation from undifferentiated stem cells was observed. When G5 was removed from the co-culture medium completely, however, the replated motoneurons survived poorly. To mediate this complication, the G5 was kept in the original plating medium for the co-culture and then was gradually removed after two days.

#### Immunocytochemistry and Microscopy

##### Materials and Methods.

Cells on DETA coverslips were fixed in freshly prepared 4% paraformaldehyde for 15 min. For the co-stainings with BTX-488, cultures were incubated with BTX-488 (Invitrogen, Cat# B13422) at 1×10<sup>-8</sup>M for 1 hr in the 37° C. incubator before fixation. Cells were then washed twice in Phosphate Buffered Saline (PBS) (pH 7.2, w/o Mg<sup>2+</sup>, Ca<sup>2+</sup>) for 10 min each at room temperature, and permeabilized with 0.1% triton X-100/PBS for 15 min. Nonspecific binding sites were blocked in Blocking Buffer (5% Donkey serum plus 0.5% BSA in PBS) for 45 min at room temperature. Cells were then incubated with primary antibodies overnight at 4° C. After

being washed with PBS 3×10 min, the cells were incubated with secondary antibodies for 2.5 hours at room temperature. The cells were then washed with PBS 3×10 min and mounted with Vectashield with 4'-6-Diamidino-2-Phenylindole (dapi) (Vector laboratories, Inc.). Primary antibodies used in this study include: Rabbit-anti-β III Tubulin (Sigma, 1:1500), Mouse-anti-synaptophysin (Antibodies Inc., 1:100). The monoclonal antibody against muscle heavy chain (MHC, F1.625, 1:10) was obtained from the Developmental Studies Hybridoma Bank which is under the auspices of the NICHD and maintained by the University of Iowa. Secondary antibodies include: Donkey-anti-Mouse-488 (Invitrogen, 1:250) and Donkey-anti-Rabbit-594 (Invitrogen, 1:250). All antibodies were diluted in Blocking Buffer.

#### Discussion.

After one week of co-culture, the morphology of hMNs and hSKM myofibers were well defined and easily distinguishable, and it was observed that the hMNs axons terminated and even branched at the contact with myofibers (FIGS. 2A, B). Utilizing immunocytochemical analysis with β-III Tubulin for neurons and muscle heavy chain (MHC) for the myofibers, the details of these contacts were confirmed. In the co-culture system the nerve endings branched in the vicinity of myotube and the terminals wrapped around the myotubes as shown in FIG. 2C. This image reproduces previous findings during NMJ formation which indicated that synaptogenesis is a dynamic process directly correlated to the active branching and remodeling of axon terminal arbors (28, 29). The potential for NMJs in the culture were further analyzed by the coimmunostaining of BTX-488 (a-bungarotoxin, Alexa Fluor® 488 conjugate) and synaptophysin, a synaptic vesicle protein. As shown in FIG. 3, synaptophysinpositive terminals co-localized with AchR clusters, a strong indication for NMJ formation.

#### Electrophysiological Properties

##### Materials and Methods.

Electrophysiological properties of spinal cord stem cell-derived motoneurons and human myotubes were investigated after ~10 days in the coculture using whole-cell patch-clamp recording techniques (26). The recordings were performed in a recording chamber located on the stage of a Zeiss Axioscope 2FS Plus upright microscope (50).

Motoneurons were identified visually under an infrared DICvideomicroscope. The largest multipolar or round cells (15-25 μm diam) with bright illuminance in the culture were tentatively identified as motoneurons (51, 52). Patch pipettes with a resistance of 6-10 MO were made from borosilicate glass (BF 150-86-10; Sutter, Novato, Calif.) with a Sutter P97 pipette puller (Sutter Instrument Company).

Current-clamp and voltage-clamp recordings were made utilizing a Multiclamp 700A amplifier (Axon, Union City, Calif.). The pipette (intracellular) solution contained (in mM) K-gluconate 140, MgCl<sub>2</sub> 2, Na<sub>2</sub>ATP 2, Phosphocreatine 5, Phosphocreatine kinase 2.4 mg, Hepes 10; pH 7.2. After the formation of a gigaohm seal and the membrane puncture, the cell capacitance was compensated. The series resistance was typically <23 MO, and it was compensated >60% using the amplifier circuitry. Signals were filtered at 3 kHz and sampled at 20 k Hz using a Digidata 1322A interface (Axon instrument).

Data recording and analysis were performed with pClamp8 software (Axon instrument). Membrane potentials were corrected by subtraction of a 15 mV tip potential, which was calculated using Axon's pClamp8 program. Membrane resistance and capacitance were calculated using 50 ms voltage steps from -85 to -95 mV without any whole-cell or series resistance compensation. The resting membrane potential

and depolarization-evoked action potentials were recorded in current-clamp mode. Depolarization-evoked inward and outward currents were examined in voltage-clamp mode.

Monitoring the contraction of human skeletal muscles in the co-culture and the determination of the effect of (+)-tubocurarine chloride pentahydrate (dtubocurarine or curare) on the NMJs by video recording

#### Discussion.

The electrophysiological properties of the MNs and myotubes in the co-culture were evaluated using voltage and current clamp recordings for each cellular component. Representative voltage-clamp and current-clamp recordings for the MNs and myotubes are shown in FIG. 4. The electrical properties of MNs in the co-culture system, such as membrane resistance, resting membrane potential, Na<sup>+</sup>/K<sup>+</sup> current amplitude, the ability to repetitively fire and the amplitude of action potential (AP), were comparable to results described previously (20, 26). The electrical properties for the myotubes were also comparable to previously published results (27).

#### Videography of NMJ Formation

##### Materials and Methods.

Functional NMJ formation was investigated in the co-culture system 1–2 weeks after MN plating utilizing video recordings. In each experiment, the coverslip in a 6-well plate was maintained in NBActiv media in a time lapse chamber (37C, 5% CO<sub>2</sub>) located on the stage of a Zeiss Axiovert microscope 200. The videos were recorded by a Hamamatsu digital camera (Model C848405G) at a frame rate of 8 frames/sec using Windows Movie Maker software. For the experiments with curare, 100 µl of the Nicotinic cholinergic antagonist, (+)tubocurarine chloride pentahydrate (also known as curare, cat. no. 93750, Sigma) (stock 250 µM, final 8 µM) was applied to the bath solution to block the acetylcholine receptors present in the NMJs. This concentration was chosen based on previous study (43).

#### Discussion.

The results obtained from several of the videos will now be discussed. In Video 1 (10 min), during the first 6 min, the myotube contracted in pulses which was recurrent approximately every 1–2 min. The contraction then stopped after this time period. In Video 2 (15 min), the contraction pulses of three spots were observed to intermittently contract. In Video 3 (15 min), myotube contraction was recorded for 7 min. The addition of Curare (5 µM) silenced the contraction. In Video 4 (22 min), myotube contraction was recorded for 11 min. The addition of Curare (5 µM) silenced the contraction.

Numerous muscle contractions in the absence of any stimulus could be observed in the co-culture approximately one week after the introduction of hMNs this was based on observations from more than 15 coverslips out of 5 independent platings. All Videograph experiments were conducted in a system in which the cultures were kept in the chamber at 5% CO<sub>2</sub> 37 C conditions. They would stop in ambient condition soon after (within minutes) being taken out of the incubator. Contractions with a constant rhythm in the hMN-hSKM co-cultures were present as in Video 2, as well as contractions exhibiting a constant pattern of intermittent pulses as demonstrated in Video 1. Video 1 indicated a myotube contracting in pulses with an approximately 1–2 min interval. These recurrent contractions lasted for 6 min and stopped thereafter. In Video 2, recorded from another site, three other areas were shown to contract on and off intermittently. The contractions in the hMN-hSKM co-culture were tested by tubocurarine for their source of initiation. As in Video 3 and Video 4, the contractions ceased after the application of 100 µl of tubocurarine (200 µM) to the culture (final 5 µM), confirming the neuronal initiation of these contractions and the formation of NMJs. This experiment with curare was repeated 4 times with the same result.

These muscle contractions revealed a few differences compared to the co-cultures of hMN with rat embryonic SKMs (14). Although studies from co-cultures of fetal rat spinal cord explant with human myoblasts consistently indicated that hSKMs didn't have spontaneous contraction and any contraction in the co-culture was an indication of innervations (16–19, 30, 31).

The present invention has been described hereinabove with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. Unless otherwise defined, all technical and scientific terms used herein are intended to have the same meaning as commonly understood in the art to which this invention pertains and at the time of its filing. Although various methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described. However, the skilled should understand that the methods and materials used and described are examples and may not be the only ones suitable for use in the invention.

Moreover, it should also be understood that any temperature, weight, volume, time interval, pH, salinity, molarity or molality, range, concentration and any other measurements, quantities or numerical figures expressed herein are intended to be approximate and not an exact or critical figure unless expressly stated to the contrary.

Further, any publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety as if they were part of this specification. However, in case of conflict, the present specification, including any definitions, will control. In addition, as noted above, materials, methods and examples given are illustrative in nature only and not intended to be limiting.

Accordingly, this invention may be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these illustrated embodiments are provided so that this disclosure will be thorough, complete, and will fully convey the scope of the invention to those skilled in the art. Therefore, in the specification set forth above there have been disclosed typical preferred embodiments of the invention, and although specific terms are employed, the terms are used in a descriptive sense only and not for purposes of limitation. The invention has been described in some detail, but it will be apparent that various modifications and changes can be made within the spirit and scope of the invention as described in the foregoing specification and as defined in the appended claims.

Any element in a claim that does not explicitly state “means for” performing a specified function, or “step for” performing a specified function, is not to be interpreted as a “means” or “step” clause as specified in 35 U.S.C. § 112, ¶ 6. In particular, the use of “step of” in the claims herein is not intended to invoke the provisions of 35 U.S.C. § 112, ¶ 6.

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TABLE 1

| Composition of Enriched Co-culture Media.                |   |               |               |                |
|--|---|---------------|---------------|----------------|
| Component  | Full Name                               | Concentration | Company       | Catalog Number |
| NEUROBASAL <sup>TM</sup> /<br>NEUROBASAL <sup>TM</sup> A |   |               | Invitrogen    | 10888/21103    |
| B27 (50X)  |   | 1X            | Invitrogen    | 17504-044      |
| Glutamax (100X)  |   | 1X            | Invitrogen    | 35050          |
| GDNF   | Glial-derived<br>Neurotrophic Factor    | 10 ng/ml      | Cell Sciences | CRG400B        |
| BDNF   | Brain-derived<br>Neurotrophic Factor    | 20 ng/ml      | Cell Sciences | CRB600B        |
| Shh  | Sonic Hedgehog, N-<br>terminal peptide  | 50 ng/ml      | R&D           | 1845-SH-025    |
| RA   | Retinoic Acid                           | 0.1 uM        | Sigma         | R2625          |
| IGF-1  | Insulin-like Growth<br>Factor-I         | 10 ng/ml      | PeproTech     | 100-11         |
| cAMP   | Adenosine 3',5'-cyclic<br>Monophosphate | 1 uM          | Sigma         | A9501          |
| CNTF   | Ciliary Neurotrophic<br>Factor          | 5 ng/ml       | Cell Sciences | CRC400A        |
| NT-3   | Neurotrophin-3                          | 20 ng/ml      | Cell Sciences | CRN500B        |
| NT-4   | Neurotrophin-4                          | 20 ng/ml      | Cell Sciences | CRN501B        |
| Vitronectin  |   | 100 ng/ml     | Sigma         | V8379          |
| Laminin  | Mouse Laminin                           | 4 µg/ml       | Invitrogen    | 23017-015      |
| G5 (100X)  |   | 1X            | Invitrogen    | 17503-012      |
| Agrin  |   | 100 ng/ml     | R&D           | 550-AG-100     |

That which is claimed is:

1. A method for forming at least one synthetic neuromuscular junction, the method comprising:

co-culturing differentiated human skeletal muscle stem cells adhered to an artificial surface and overlaid with differentiated human spinal cord stem cells in a serum-free medium; and

forming at least one functional neuromuscular junction between a differentiated human skeletal muscle stem cell and a differentiated human spinal cord stem cell.

2. The method of claim 1, further comprising adding NbActiv4 to the serum-free medium.

3. The method of claim 1, wherein the artificial surface comprises a silicon based substrate monolayer deposited thereon.

4. The method of claim 3, wherein the silicon based substrate monolayer comprises DETA.

5. The method of claim 3, wherein the silicon based substrate monolayer is deposited on the artificial surface in a predetermined pattern.

6. A method of forming synthetic neuromuscular junctions, the method comprising:

adhering differentiated human skeletal muscle stem cells to an artificial surface;

overlayering differentiated human spinal cord stem cells onto the differentiated human skeletal muscle stem cells;

culturing the artificial surface in a serum-free medium, and monitoring for formation of functional neuromuscular junctions.

7. The method of claim 6, wherein the artificial surface is coated with DETA.

8. The method of claim 6, further comprising adding NbActiv4 to the serum-free medium.

9. A co-culture for forming at least one synthetic mammalian neuromuscular junction, comprising: differentiated human skeletal muscle stem cells adhered to an artificial surface and overlaid with differentiated human spinal cord stem cells in a serum-free medium.

10. The co-culture of claim 9, wherein the medium comprises the components in Table 1.

11. The co-culture of claim 9, wherein the serum-free medium comprises at least one synaptogenesis promoting component and one or more trophic factors.

12. The co-culture of claim 9, wherein one or more of the differentiated human spinal cord stem cells is functionally linked to one or more of the differentiated human skeletal muscle stem cells.

13. The co-culture of claim 9, wherein the artificial surface comprises a silicon based monolayer substrate deposited thereon.

14. The co-culture of claim 13, wherein the silicon based monolayer substrate is deposited in a predetermined pattern.

15. The co-culture of claim 13, wherein the silicon based monolayer substrate comprises DETA.

16. The co-culture of claim 9, wherein the serum-free medium further comprises NbActiv4.

\* \* \* \* \*